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Vegetation and Topographic Control of Wind-blown Snow Distributions in Distributed and Aggregated Simulations for an Arctic Tundra Basin

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ABSTRACT

A fine-scale model of blowing snow is used to simulate the characteristics of snowcover in a low-Arctic catchment with moderate topography and partial shrub cover. The influence of changing shrub characteristics is investigated by performing a sequence of simulations with varying shrub heights and coverage. Increasing shrub height gives an increase in snow depth within the shrub-covered areas, up to a limit determined by the supply of falling and blowing snow, but increasing shrub coverage gives a decrease in snow depths within shrubs as the supply of blowing snow imported from open areas is reduced. A simulation of snow redistribution over the existing topography without any shrub cover gives much greater accumulations of snow on slopes in the lee of the prevailing wind than on windward slopes; in contrast, shrubs are able to trap snow on both lee and windward slopes. A spatially aggregated, or tiled, model is developed in which snow is relocated by wind transport from sparsely vegetated tiles to more densely vegetated tiles. The vegetation distribution is not specified, but the simulation is parametrized using average fetch lengths along the major transport axis. The aggregated model is found to be capable of matching the average snow accumulation in shrub and open areas predicted by the distributed model reasonably well but with much less computational cost.

1. Introduction

Snow in open, windswept environments is subject to significant redistribution during and after snowfall. Snow is eroded from sparse or low vegetation and exposed sites and transported to denser, taller vegetation and to topographic depressions; the characteristics and spatial arrangement of vegetation and topography therefore control the evolution of snow depth and water equivalent patterns during accumulation. Knowledge of snow transport processes is required for management of snow water resources and hazards, but snow depth and mass distributions also have important influences on climate and ecology. Snow redistributed to shrubs in the low Arctic contains high chemical loads of essential plant nutrients such as inorganic nitrogen, and shrubs have deeper snow than adjacent sparsely vegetated tundra (Pomeroy et al. 1995). Snow cover provides a direct physical protection to plant stems from abrasion by blowing snow grains, and deeper snowpacks reduce overwinter soil desiccation by weakening temperature gradients in snow and soil (Pomeroy and Brun 2001). Sturm et al. (2001a) suggested that insulation due to the increased snow depth in shrub patches could lead to a positive feedback enhancing shrub growth, and Sturm et al (2001b) found a widespread increase in Alaskan shrub cover over the last 50 years from pairs of aerial photographs. Recent expansions of woody vegetation have also been observed in alpine tundra areas (Kullman 2002; Sanz-Elorza et al. 2003). Much work has been done at the plant, stand and process scale on the influence of snow on vegetation distributions (Walker et al. 2001), and on the influence of vegetation on redistribution of snow (Tabler and Schmidt 1986; Pomeroy and Gray 1995; Pomeroy and Marsh 1997), but further investigations of interactions between vegetation and wind-blown snow over larger spatial scales that approximate a meso-scale catchment or climate model grid cell are required. In particular, though landscape units with characteristic snow accumulation characteristics have been long identified in most major biomes (e.g. Kuz'min 1960; Gray et al. 1979), the influence of topography, climate and other factors on the coevolution and persistence of snow accumulation and vegetation patterns needs further elucidation.

Several models have been developed to simulate the redistribution of snow by wind over landscapes with variable vegetation or topography represented by high-resolution grids (Pomeroy et al. 1997; Liston and Sturm 1998; Purves et al. 1998; Gauer 1998; Essery et al. 1999). Blowing snow processes have so far been neglected in large-scale climate models, but they may play an important role in the water, atmospheric moisture and energy budgets of snow-covered regions (Pomeroy and Li 2000; Déry and Yau 2001); sublimation of blowing snow returns moisture to the atmosphere, and horizontal transport of snow generates spatial variations in snow depth that lead to patchy cover and strong heterogeneities in surface characteristics during melt. Redistribution of wind-transported snow between catchments can strongly affect the water balance at small scales (Marsh et al. 1995; Pomeroy and Li 2000), and the combination of redistribution and sublimation loss has an important control on spring runoff generation (Marsh and Pomeroy 1996). Simulations at meso-scales show the importance of blowing snow process to large scale water balances and hydrology (Liston and Sturm 2002; Bowling et al. 2004). The use of high-resolution distributed models to represent blowing snow processes within large-scale models, however, is impractical because of their computational expense.

This paper seeks to promote further understanding of the interaction between the atmosphere, blowing snow, topography and vegetation in a complex low-Arctic landscape through numerical experiments that estimate the sensitivity of resulting snow distributions to variations in shrub cover and topography. A distributed blowing snow model is used with meteorological observations and digital maps of vegetation and topography to simulate snow depth patterns. The height and density of shrub cover are varied in simulations to investigate the influence of vegetation distributions on snow distributions. Simulations with the same topography but no tall vegetation, and the same vegetation distribution but on a flat plane, are performed to compare the influences of vegetation and topography. As the influence of vegetation cover on snow water equivalent is demonstrated to be quite large in this environment, results from a more efficient spatially aggregated version of the blowing snow model that ignores topographic effects on wind speed and simply divides the landscape into open and shrub-covered areas are compared to aggregated results from the fully distributed model. The aggregated model is finally used to evaluate the sensitivity of seasonal blowing snow sublimation losses to variation in estimates of the rate of instantaneous sublimation.

2. Site, observations and model descriptions

Trail Valley Creek (68º44′N, 133º29′W) is a low-Arctic tundra catchment in northwest Canada, 50 km north of Inuvik, Northwest Territories. A map of vegetation cover and a digital elevation model for this region were derived from a supervised, field verified classification of a LANDSAT TM and a digitised topographic map (Pomeroy and Marsh 1997). Figure 1 shows the topography and vegetation of a 14 km x 12 km area; open tundra and lakes cover 71% of the area, and areas of taller vegetation are shown shaded on Fig. 1. Exposed plateaus are covered with open tussock tundra and bare ground, whereas shrubs (alder and willow) and sparse spruce stands are mostly confined to moister slopes, valley bottoms and the fringes of lakes. Many of the factors determining vegetation distributions, including slope, aspect, wind exposure, soil moisture, active layer depth in permafrost, soil structure, fire history, nutrient availability and the location of late-lying snow drifts, are influenced by topography and winter wind direction (see e.g. Walker et al. 2001). For an Alaskan tundra catchment, Ostendorf and Reynolds (1998) found that the vegetation distribution could be predicted with an accuracy of 73% using a topographic wetness index (Quinn et al. 1991). Although the relationship between the location of shrubs and this particular topographic index is less strong for Trail Valley Creek, there is still a clear association between vegetation distribution and topography in Fig. 1.

Surveys of snow depth and density in open and shrub-covered areas of Trail Valley Creek were performed in April of 1993, 1996 and 1997 before melting had begun and were used to calculate landscape-based means and standard deviations of snow water equivalent (SWE) or snow mass on the ground (mm or kg m^{-2}). Seasonal snowfall was estimated from the average accumulation in a small glade within a sparse forest stand that undergoes minimal snow redistribution. Half-hourly measurements of windspeed, temperature, humidity, snow particle flux and snow depth were collected at an open, level site in the catchment over the winter of 1996-97. Half-hourly snowfall was estimated from changes in snow depth, fluxes of falling or blowing snow particles measured by the snow particle detector and monthly snowfall accumulations in a nipher-shielded snowfall gauge to which corrections for wind induced undercatch were applied (Pomeroy and Li 2000). Table 1 shows air temperature, relative humidity with respect to ice, windspeed and snowfall for each month between September 1996 and March 1997. Measured humidities were frequently close to ice saturation, but these measurements are likely to be overestimates as the hygrometer was prone to icing during long periods of unattended operation, introducing uncertainty in model calculations of sublimation (Déry and Stieglitz 2002). There was also a 10-day period without wind measurements due to equipment failure in December 1996; the average wind in Table 1 excludes those days.

The meteorological observations were used to drive a distributed blowing snow model for the period 11 September 1996 to 8 April 1997**.** The model, described in detail by Essery et al. (1999), is based on a simplified version of the Prairie Blowing Snow Model (Pomeroy et al. 1993; Pomeroy and Li 2000) that predicts fluxes of snow transport and in-transit sublimation for long unvegetated fetches using observations of snowfall, air temperature, humidity and windspeed. Temperature, humidity and snowfall are assumed to be homogeneous over the model domain. Spatial variations in windspeed due to variations in surface roughness are also neglected, but variations due to topography are predicted using the MS3DJH terrain windflow model (Walmsley et al. 1986). For vegetated surfaces, the windspeed used in calculating blowing snow fluxes is reduced to

$$U_s = \frac{U}{(1 + 340 z_0)^{1/2}} \tag{1}$$

using the stress partitioning scheme of Raupach et al. (1993), where U is the unadjusted local windspeed simulated by MS3DJH and z_0 is the roughness length for vegetation exposed above the snow; Lettau (1969) gives

$$z_0 = \frac{Ndh}{2} \tag{2}$$

for vegetation with stalk diameter d, stalk density N and exposed height h. Unvegetated surfaces are given a roughness of 10^{-3} m. The approach to equilibrium downwind of a change in surface characteristics is represented by a horizontal flux development scheme based on observations by Takeuchi (1980); local transport and sublimation fluxes are adjusted to follow

$$q = Q - \frac{F}{3}\frac{\partial q}{\partial x}, \tag{3}$$

where Q is the fully-developed flux for fetch $F = 1000$ m and x is distance along an axis aligned with the wind. The spatial distribution of redistributed snow is quite sensitive to the shape of this curve.

The Trail Valley Creek area is divided into an 80 m × 80 m grid with the structure shown in Fig. 2a. Changes in SWE with time within each gridbox are calculated using a discretized version of the differential equation

$$\frac{\partial S}{\partial t} = S_f - q_s - \nabla \cdot q_t, \tag{4}$$

where S is the SWE, S_f is the snowfall rate, q_s is the sublimation rate and $\nabla \cdot q_t$ is the horizontal divergence of the transport.

The distributed blowing snow model uses a grid of 26250 boxes to represent the Trail Valley Creek area. This is clearly impractical for large-scale modelling applications; the

HadCM3 climate model (Pope et al. 2000), for example, uses 2381 grid boxes to represent the entire global land surface. Spatially aggregated, landscape-based blowing snow models, previously demonstrated by Pomeroy et al. (1991, 1997) and Pomeroy and Li (2000), are more efficient. The structure of an aggregated version of the blowing snow model is shown in Fig. 2b. For this model, the landscape is assumed to consist of alternating strips of open ground and shrubs with average lengths l_o and l_s measured from the vegetation map along the prevailing wind direction. This is similar to the "mosaic" structure often used in land-surface models to represent subgrid variations in vertical fluxes of heat and moisture (Avissar and Pielke 1989; Koster and Suarez 1992; Essery et al. 2003) but is adapted to include horizontal transport of snow between landscape classes. Pomeroy et al. (1997) used a similar approach in the Arctic, mapping the simulated snow accumulation in vegetation classes back onto the landscape to give a partially distributed simulation. The approach was also used by Pomeroy et al. (1991, 1993), Pomeroy et al. (1998) and Hedstrom et al. (2001) in prairie, forest clearing and alpine environments using the full PBSM model.

The aggregated model ignores topographic effects on wind speed and simply divides the landscape into open and shrub-covered areas with characteristic fractions and length scales. Solving Eq. (3) for transport fluxes across boundaries between homogeneous landscape classes gives the net transport into shrubs as

$$q_t^o - q_t^s = \frac{ab(Q_t^o - Q_t^s)}{1-(1-a)(1-b)}, \tag{5}$$

where a=1-exp(-3l_o/F) and b=1-exp(-3l_s/F). The 'o' and 's' superscripts denote open and shrub classes, and Q_t is the fully-developed transport flux calculated by the one-dimensional blowing snow model for each class. Similarly, the average sublimation fluxes are found as

$$q_s^o = Q_s^o + \frac{F}{3l_o}\frac{ab(Q_s^s - Q_s^o)}{1-(1-a)(1-b)} \tag{6}$$

for open areas, and

$$q_s^s = Q_s^s + \frac{F}{3l_s}\frac{ab(Q_s^o - Q_s^s)}{1-(1-a)(1-b)} \tag{7}$$

for shrubs. Discretizing Eq. (4), the mass budgets for the open and shrub classes are

$$\frac{dS^o}{dt} = S_f - q_s^o + \frac{q_t^s - q_t^o}{l_o} \tag{8}$$

and

$$\frac{dS^s}{dt} = S_f - q_s^s + \frac{q_t^o - q_t^s}{l_s}. \tag{9}$$

Pomeroy et al. (1997), using manual ruler measurements and a less accurate vegetation/slope classification, determined the average shrub patch size along NW-SE transects across Trail Valley Creek to be 500 m. Measuring the size of the shrub patches numerically at the resolution of the distributed model gives a smaller average, 240 m, which is taken as the value for l_s here. The difference in estimates is likely to be due to differing shrub classification criteria and the commonly observed fact that the average size measured for a distribution of natural objects depends on the spatial resolution of the measurements. The patch size for open areas is given by

$$l_o = \frac{(1 - f_s)}{f_s} l_s \tag{10}$$

for shrub fraction f_s

3. Influences of shrub height, shrub distribution and topography on snow accumulation

Plotting observations of seasonal maxima in areal-average SWE against seasonal snowfall for the three years of snow surveys shows that the shrub snow accumulation exceeded the snowfall in each year but levelled off for greater snowfall years (Fig. 3). Similar consistency of snow accumulation in tall vegetation is found in steppe and prairie environments (Tabler and Schmidt 1986; Pomeroy and Gray 1995). The accumulation in open areas was less than the snowfall in each year but shows no clear relationship with snowfall; it appears that the open tundra in the area surveyed can hold about 70 mm of SWE, with excess snow being removed by wind.

The distributed model was first run in a control simulation using nominal and uniform 1 m shrub heights and stalk area densities Nd = 0.1 estimated from field observations (Pomeroy and Li 2000). Figure 4a shows a map of SWE at the end of this simulation; the snow distribution is strongly controlled by the vegetation distribution due to trapping of wind-blown snow by shrubs. The average SWE of 219 mm for areas with shrub cover matches the average from surveys carried out on 23 April 1997, but the simulated 57 mm accumulation for open areas is less than the observed 86 mm. The shrub accumulation is greater than, and the open accumulation is less than, the estimated 179 mm snowfall because snow is blown off open areas and trapped by shrubs. The simulated SWE standard deviation of 26 mm for shrubs is quite different to the 42 mm calculated from the survey, but these numbers are not directly comparable due to spatial correlations in SWE. The model represents the average SWE in 80 m × 80 m boxes and samples 7031 boxes with shrub cover, whereas the 1997 surveys consisted of 130 point depth measurements with spacings between 1 m and 5 m over 250 m lines and densities measured every 50 m. The simulated SWE values thus have a wider support (area averages rather than point measurements), which reduces the standard deviation, and a greater extent (sampled over a larger area), which increases the standard deviation (Western and Blöschl 1999). Fitting an exponential function to the variogram of the shrub survey data gives a correlation length of 6 m. Using the method of Western and Blöschl (1999) to aggregate the observations to the model grid scale reduces the observed standard deviation to 7 mm. Conversely, restricting the sample of model gridboxes to a 240 m extent in the area around the location of the survey reduces the simulated standard deviation to 10 mm. It is likely, in any case, that the modelled variance would differ from observations as the model does not capture fine-scale variations around vegetation and uses single values for shrub height and density. Observations in prairie environments show that snow depth varies at both small and medium scales with vegetation height if there is sufficient wind-blown snow to fill in the vegetation completely and if strong winds do not scour snow from the vegetation (Pomeroy and Gray 1995). It would be possible to incorporate maps of vegetation characteristics in the model if they were available from some remote-sensing source such as SAR or LIDAR (Schmugge et al. 2002). Although predictions of average SWE are useful, the standard deviation is also required for snowmelt models, as this determines the timing and rate at which snow-free ground emerges during melt (Donald et al. 1995).

Lacking the detailed meteorological data required to run the model for other years, a sequence of simulations was performed using the meteorological observations for 1996-1997 but varying the snowfall rates during the observed events to give different seasonal totals. The varying SWE in shrubs and open areas for these simulations are shown by lines on Fig. 3. The shrub accumulation shows an increasing trend with snowfall, similar to the observations, but the simulated accumulation in open areas shows a stronger trend than observed. Although the simulated accumulation is similar to the observation for 1997, and comparisons with other years should be made with caution as only the snowfall rate was adjusted, it appears that the model does not hold enough snow in open tundra for low snowfall years. This is probably because trapping by small-scale topographic and vegetative features is not represented; sparse vegetation, small depressions and exposed boulders trap snow in open tundra, and deep drifts form in Trail Valley Creek with widths of around 20 m, which cannot be captured by the model's 80 m grid. These effects could be partially parametrized by defining a sub-grid topographic holding capacity, analogous to the vegetation holding capacity of Liston and Sturm (1998), from a higher resolution DEM.

To investigate the influence of vegetation, a sequence of simulations was performed in which the shrub height was varied. Spatial averages and standard deviations of the SWE for shrubs and open areas at the end of each simulation are shown in Fig. 5. For open areas, the average SWE and standard deviation vary little with shrub height. The average shrub SWE initially increases with increasing shrub height as the potential of the shrubs to trap wind-blown snow increases, but this is eventually limited by the supply of snow. Shrubs with the 1 m height used in the control simulation trap nearly the maximum possible amount of snow, corresponding to a depth of about 75 cm. The suppression of blowing snow by increasing shrub heights also reduces the standard deviation of SWE, although in reality this reduction would be limited by the small scale variability of shrub height. Liston et al. (2002), using a similar modelling strategy, found a similar increase in shrub SWE with increasing holding capacity but did not report a maximum in accumulation. Sturm et al. (2001a), however, reported a large increase in observed snow depth with a small increase in vegetation height and density from tussock tundra to shrubby tussock tundra but only a small increase in snow depth with a further increase in density and height to riparian shrubs. Similarly, Pomeroy and Gray (1995) reported a rapid drop in blowing snow transport for Regina, Saskatchewan, as wheat stubble height increased from 1 to 5 cm, with a relatively small reduction as stubble height increased further. Trapped snow insulates shrubs from wind, snow particle abrasion, desiccation and low air temperatures; shrubs taller than those which just trap all the available snow will suffer greater exposure. It is likely that natural vegetation heights in such extreme environments are governed to some degree by the maximum snow depth possible from snowfall and blowing snow transport inputs. The stability of this maximum snow trapping by shrubs with changing winter meteorology warrants further investigation that is outside the scope of this paper.

The extent of shrub cover was increased or decreased in a sequence of simulations by progressively adding or removing shrubs in model gridboxes around the edges of existing shrub patches. Although this method takes no account of ecology, it is plausible that natural changes in shrub cover would largely proceed by expansion or contraction of existing patches. As the coverage is increased from the observed fraction of 29%, the supply of wind-blown snow from open areas and the average SWE in the shrubs decreases, as shown in Fig. 6. For very large shrub fractions, the average SWE falls below the amount of snowfall because of sublimation losses. Suppression of blowing snow again gives a decrease in SWE standard deviation as the shrub fraction increases, increasing the homogeneity of the landscape. The average and standard deviation of SWE in open areas also both decrease with increasing shrub fraction as the remaining open areas are progressively confined to flatter but more windswept plateau areas.

To compare the influences of vegetation and topography on snow distributions, the control simulation was repeated with the same vegetation distribution but on a flat plane (no topography), and the same topography but without vegetation. Snow distributions at the end of these simulations are shown in Figs 4b and 4c respectively. Vegetation distributions are strongly related to topography, so the simulation without topography is only intended to illustrate the influence of vegetation on snow accumulation in this environment, not the pattern of accumulation that might be expected in a similar environment with low relief. Because shrubs have a strong control on the snow redistribution and the topography is moderate, the simulation without topography gives a very similar pattern of snowcover to the control. The topography *does* strongly influence the distribution of snow in the simulation without vegetation, however, with drifts forming on valley slopes in the lee of the prevailing northwesterly wind; Fig. 7a shows a wind rose for the frequency of strong winds exceeding 6 ms^{-1} that are responsible for the majority of the snow transport. Because the shrubs are largely confined to the valleys, there are some similarities between the snow distributions determined by vegetation alone and by topography alone. The influence of topography can be clearly seen in Fig. 7b, which shows the average SWE on slopes of greater than 9° as a function of aspect. Without vegetation, the snow loading is much greater on slopes in the lee of the prevailing northwesterly wind than on windward slopes. In the control simulation, the average SWE on the lee slopes is similar, but trapping of snow by shrubs increases the snow depth on slopes with other aspects.

4. Vegetation-based aggregated blowing snow model

The similarity of predictions of blowing snow redistribution obtained using vegetation alone to those using both vegetation and topography in this environment suggests that simplified estimation procedures based on the spatial distribution of vegetation might be sufficient for areally averaged predictions. Predictions from the aggregated model for SWE in shrubs and open areas are shown by lines on Fig. 5; a reasonable agreement is obtained with averaged results from the distributed model. As shown by the dotted lines on Fig. 3, the aggregated model also matches the results from the distributed model for varying amounts of snowfall.

The procedure used above to change the fraction of shrub cover is found to give average shrub patch sizes approximately related to the fraction of shrub cover by $l_s \approx 81\exp(3.5f_s)$. Using this relationship to parametrize the patch length scales, the aggregated model again gives reasonable matches with distributed simulations of SWE for varying shrub cover, as shown in Fig. 6. When one class is dominant, the errors are larger for the minority class; this type of behaviour is common in mosaic models of surface energy balance (Liston 1995) and gives less error in area-averages; the dotted line and open diamonds on Fig. 6 show a close agreement between area-average SWE predicted by the distributed and aggregated models.

5. Sublimation of blowing snow

The difficulty of obtaining reliable meteorological measurements throughout the winter in harsh environments and the complexity of the processes involved make the prediction of sublimation in blowing snow difficult. Mass balance studies have, however, suggested that sublimation can be responsible for significant losses of snow mass. Benson (1982) used surface snow and snowfall measurements to estimate snow redistribution along the Arctic coast of Alaska and found that 58% of annual snowfall remained on the tundra, 11% was transported to form drifts in a river valley and 32% was unaccounted for and presumed to have sublimated in transit. Pomeroy and Gray (1995) used a blowing snow model to estimate that over unvegetated fallow fields on the Canadian Prairies for a seven year period, 23%-41% of seasonal snowfall sublimated during blowing snow transport, but with a 25 cm tall wheat stubble on the fields these losses dropped to 15%-34% of snowfall; transport losses from the fields were 13%-36% of snowfall from fallow and 8%-21% from stubble. These model results were evaluated for high and low snowfall years against field observations of snow mass balance and found to provide a good match (Pomeroy and Li 2000). For Trail Valley Creek, Essery et al. (1999) performed a sensitivity test with the distributed blowing snow model by suppressing sublimation; this led to excessive snow accumulations in areas of tall vegetation.

There has been much discussion of the extent to which sublimation of blowing snow is limited by the consequent moistening of the air (Xiao et al. 2000; Pomeroy and Li 2000; Bintanja 2001); this is not explicitly represented by the blowing snow model used here, but the model is based on actual humidity profiles measured during blowing snow events (Pomeroy et al. 1993). The amount of sublimation during a single event will be controlled by the rate of entrainment of dry air at the top of the layer of blowing snow (Bintanja 2001), but it is possible that vegetation trapping could limit the sensitivity of sublimation on seasonal time scales to the model formulation; a model with a lower instantaneous rate of sublimation will leave more snow available for sublimation in subsequent events once the snow depth exceeds the holding capacity of the surface. This can be investigated in either the distributed or aggregated model by scaling the sublimation calculated at each timestep by some multiplicative factor. Figure 8 shows how the total sublimation in the aggregated model varies with scaling factors between 0 and 1.5; the total sublimation is normalized by the sublimation predicted by the un-scaled model. It can be seen that a lowering or raising of the instantaneous sublimation rate does not quite give a proportionate lowering or raising of the seasonal sublimation. For example, between scaling factors of 0.5 and 1.5 there is only a 224% increase in seasonal sublimation for a 300% increase in sublimation rate. The seasonal sublimation is therefore less sensitive than the instantaneous sublimation to the model formulation and uncertainties in humidity measurements.

6. Conclusions

A distributed simulation of transport and sublimation of blowing snow over a low-Arctic tundra basin gave a snow distribution that was strongly controlled by the vegetation distribution, with shrubs trapping snow blown off open areas. The average snow accumulation was in close agreement with observations from snow surveys in shrubs, but the simulated standard deviation had to be adjusted to allow for the different measurement and simulation scales and spatial variations in vegetation characteristics. The agreement between simulations and observations of average SWE in open areas was less good, possibly because unresolved topographic variations have a greater influence on accumulation in these areas.

Up to a threshold height determined by the supply of snow, increasing the shrub height in simulations increased the amount of snow held by shrubs and decreased its spatial variance. Shrubs of the observed height trapped close to the maximum possible amount of snow for the winter studied. Increasing the coverage of shrubs decreased the amount of snow held in shrubs and decreased its variance.

Although the snow distribution is strongly controlled by vegetation, the influence of topography was apparent in the accumulation of snow on lee slopes. Comparing simulations with and without vegetation showed that shrubs can also increase the snow depth by trapping on windward slopes. Hiemstra et al. (2002) came to similar conclusions from simulations of snow distributions with and without trees at a treeline site.

High-resolution distributed models are impractical for use in large-scale modelling applications. An aggregated model for the average accumulation in shrubs and open areas with length scales and fractions measured from the vegetation map was developed. The aggregated model gave good agreement with average results from distributed simulations with varying shrub heights and fractions. The success of the aggregated model is due to the strong control of vegetation on simulated snow redistribution in this environment. In environments where snow distributions are strongly controlled by topography, it may be possible to use an aggregated model with landscape units based on wind exposure instead. The parametrization of topographic variations in windspeed over Trail Valley Creek was discussed by Essery (2001) and applied in a blowing snow model by Bowling et al. (2004). The influence of wind transport on subgrid snow distributions could also be represented implicitly using a snowcover depletion curve with a width dependent on the degree of redistribution (Essery and Pomeroy 2004; Liston 2004).

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	Average temperature (°C)	Average relative humidity (%)	Average windspeed (ms^{-1})	Total snowfall (mm)
September	-1.2	95	5.1	35
October	-13.1	97	3.8	31
November	-18.6	97	3.8	16
December	-23.6	99	4.6	18
January	-26.7	97	3.7	11
February	-24.9	98	3.6	26
March	-25.1	95	6.1	36

Table 1

Meteorological observations for the winter of 1996-1997.

FIGURE CAPTIONS

Figure 1

Topography (20 m contour interval) and surface cover of Trail Valley Creek, showing areas of tall vegetation in grey. The area shown is 14 km by 12 km and has a 140 m range in elevation.

Figure 2

Grid structure of (a) the distributed model and (b) the aggregated model.

Figure 3

Average SWE in shrubs (♦) and open areas (▲) from April snow surveys in 1993, 1996 and 1997. Solid and dotted lines were produced by the distributed and aggregated models, respectively, with 1996-97 meteorology but varying snowfall rates. The 1:1 line is dashed.

Figure 4

SWE distributions in (a) the control simulation and simulations (b) without topography and (c) without vegetation.

Figure 5

Average and standard deviation of simulated SWE for shrubs (♦) and open areas (▲) as shrub height is varied. Crosses show observations from surveys on 23 April 1997, and the dashed line shows total snowfall. Solid lines show results from the aggregated model.

Figure 6

As Fig. 5, but for distributed and aggregate simulations with varying shrub fractions. Area-average SWE is shown by the dotted line for the distributed model and open diamonds for the aggregated model.

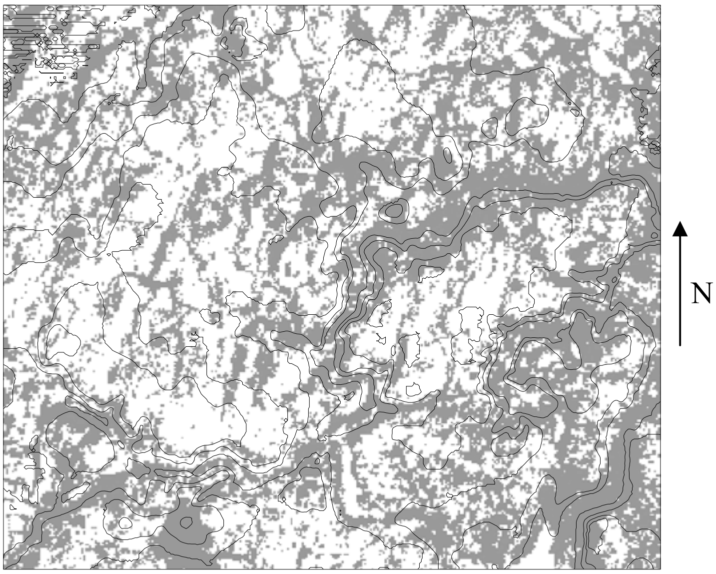
Figure 7

(a) Average SWE (mm) on slopes of different aspect in the control simulation (thin line) and the simulation without vegetation (thick line).

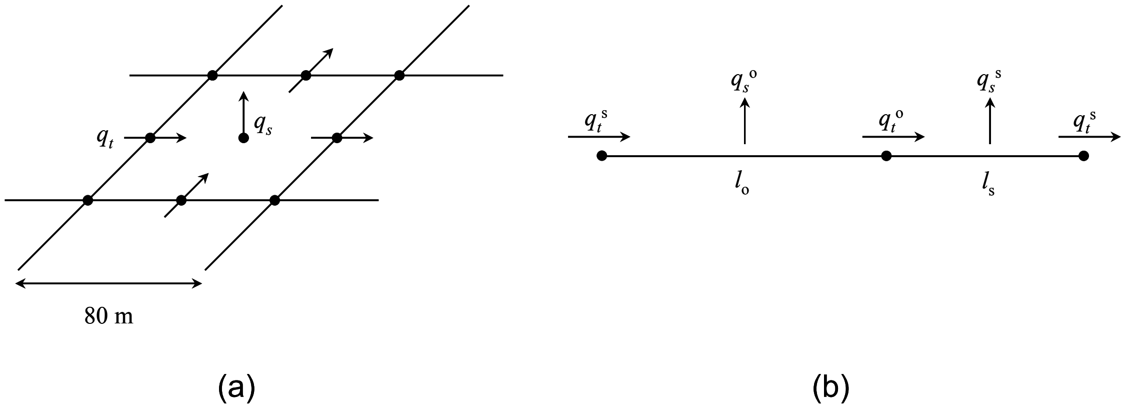
(b) Wind rose for winds exceeding 6 ms^{-1}.

Figure 8

Variation in simulated seasonal sublimation (solid line) as the instantaneous sublimation rate is varied by a scaling factor. The dashed line shows proportional scaling.



Essery and Pomeroy, Figure 1.



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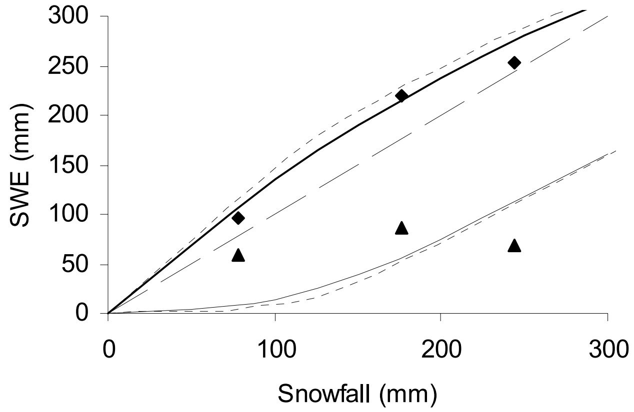

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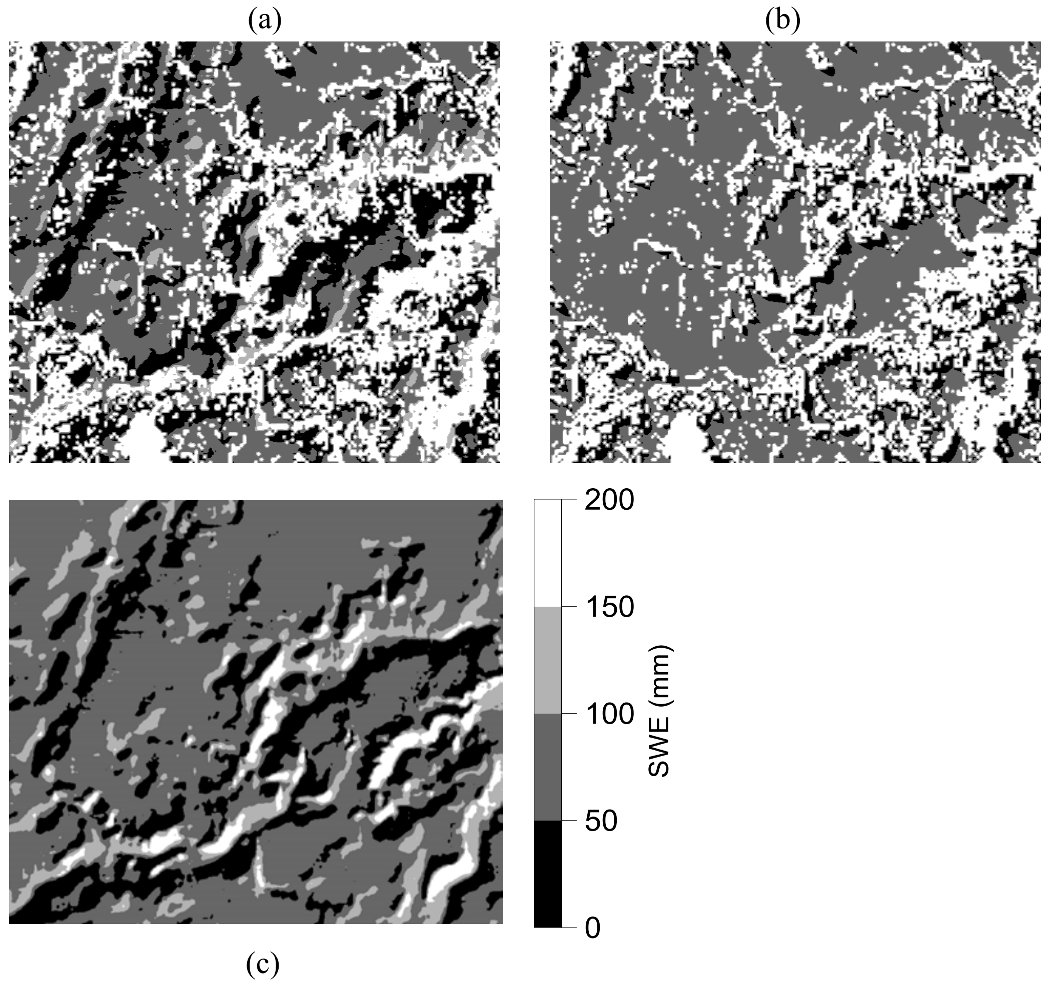

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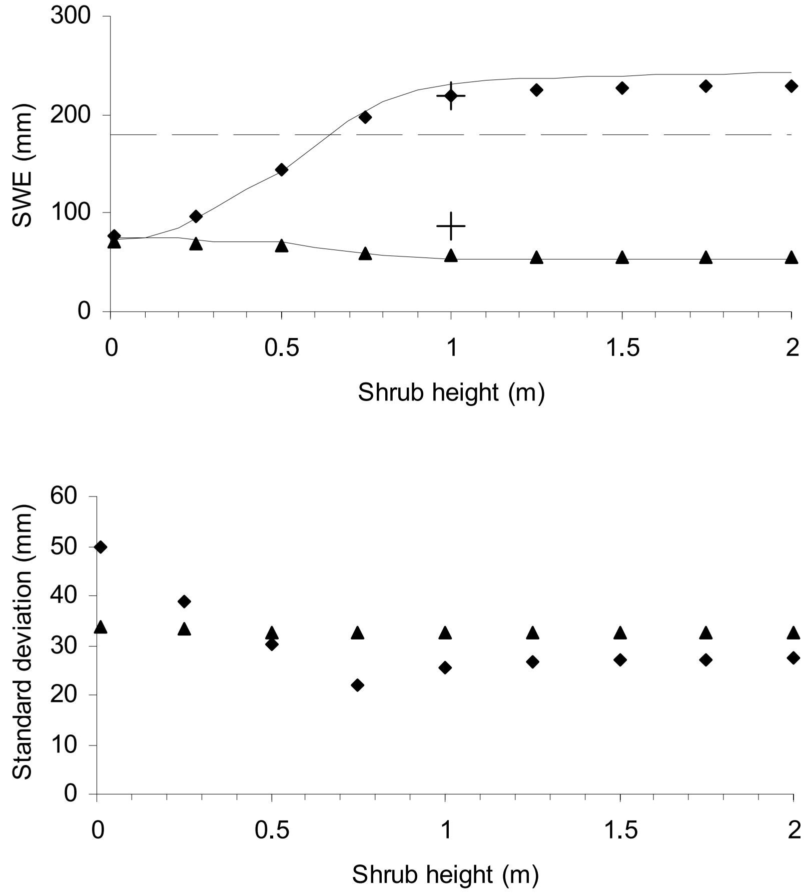

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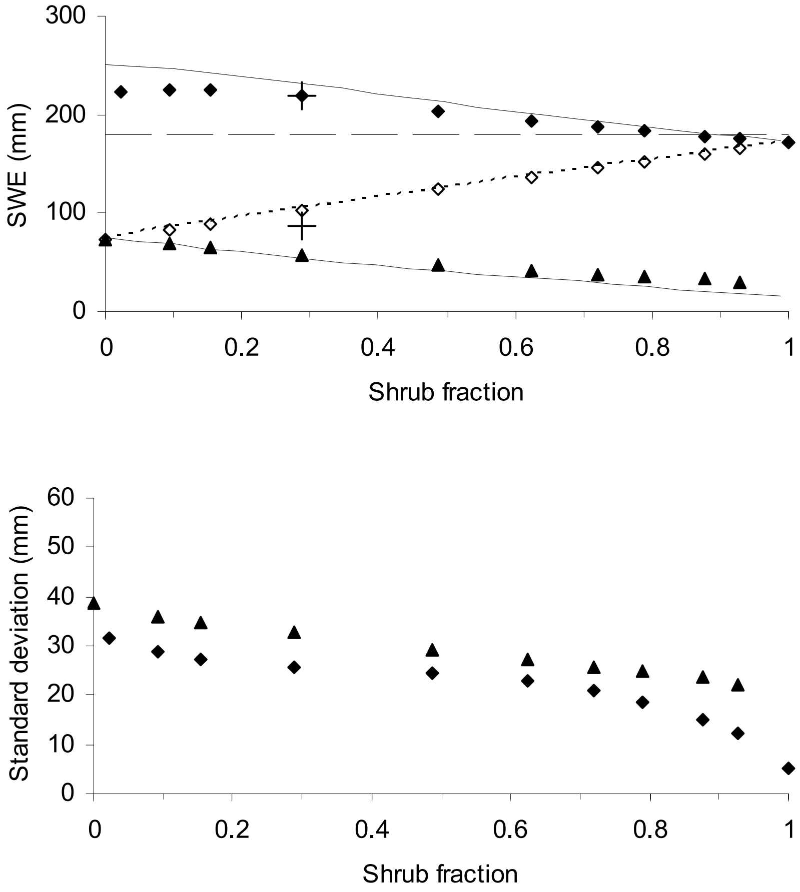

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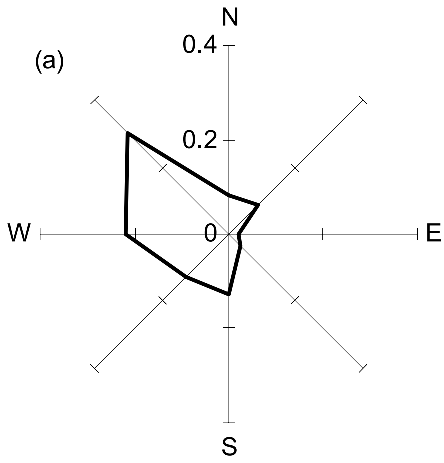
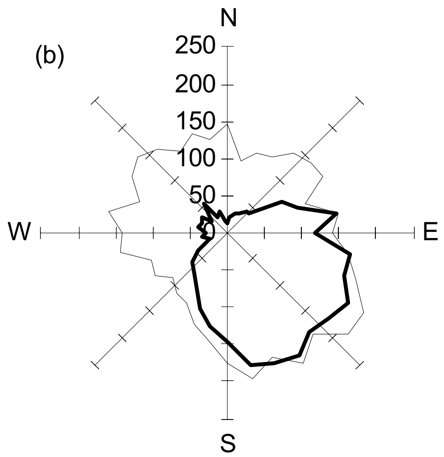
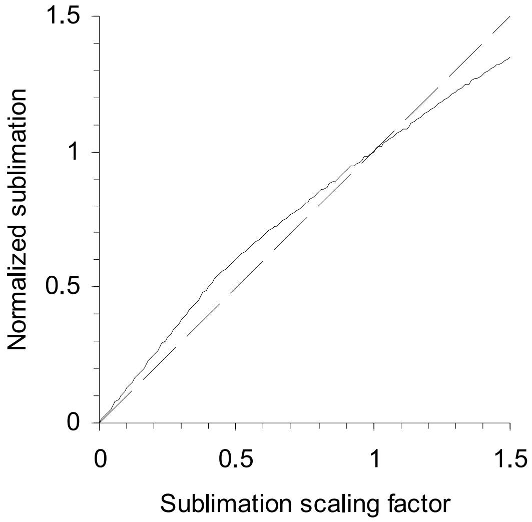




Essery and Pomeroy, Figure 7.



Essery and Pomeroy, Figure 8.